Design of Regenerative Braking System and Energy Storage with Supercapacitors as Energy Buffers

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Abstract *– Vehicles are part of urban area transport and are subjected to variable loads as they traverse the city with varying slopes and stop-and-go traffic. Electric Vehicles (EVs) can be a good option because of their high efficiency under stop-and-go conditions and ability to gain energy from braking. However, limited battery energy makes EVs less efficient and degrades their lifetime. In contrast to a Li-Ion battery, supercapacitors work well under high power charge and discharge cycles. However, their high cost and low energy density prevent them from being viable replacements for batteries. Due to the slow charging and discharging process of batteries, they have a low power density, but a high energy density compared to the supercapacitor. In this paper, we discussed our system design consisting of both a battery and a supercapacitor. The main aim is to design and develop a scheduling algorithm to optimize energy flow between the battery, supercapacitor, and motor. We further described an analogue-based control methodology and algorithm for the supercapacitor, augmented battery-powered motoring process. This is in addition to a charge controller designed to optimize the supercapacitor bank's current-based charge-discharge profile. The system design and tests are developed on PSPICE and a hardware platform.*

Keywords: *Energy storage, Supercapacitors, Energy buffers, Regenerative braking systems, Electric vehicles, scheduling algorithm, DC-DC converter*

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1. INTRODUCTION

An increase in the percentage of the emissions of hazardous greenhouse gases and other pollutants comes from high road traffic transportation systems. Carbon emissions could be reduced using electric vehicles. However, there have been some limitations over EVs, like energy backup, which depends on battery power. Power management systems involving supercapacitors have been of great interest in the power engineering arena, and various control approaches and topologies have been proposed for numerous supercapacitor-augmented applications [1-15]. With the advancement of Energy Storage Systems (ESSs), several proposals have emerged for managing and designing such systems. Some work have detailed the comparison of the ESSs, which can be found in Ref. [16]. Recently, the concept of Hybrid ESSs has emerged. This concept combines two or more ESSs to benefit from their complementary characteristics [17-

19]. Sang Young Park et al. [20] proposed an electronic-based power interface for supercapacitor-based hybrid energy storage systems and battery management for electric vehicles. The effectiveness of the supercapacitor-based HESSs has been demonstrated in a large number of research works, showing improved performance in terms of acceleration of the EV [17], energy efficiency during regenerative braking [9], driving range of the EV [2,6], and the lifetime of battery [21-24]. In addition, other noticeable research is outlined in [25-28], which has made many contributions to this field.

To this end, we developed a new control strategy for a supercapacitor-battery vehicle. It is anticipated that the hybrid power source with a combination of a supercapacitor bank and Lithium-Ion battery will improve the range and efficiency of the vehicle by charging the battery through the supercapacitor. The energy generated from regenerative braking and the advantageous features of supercapacitors are defined as essential metrics for propulsion.

Supercapacitors have a very high specific power (W/kg). Its augmentation into battery-powered motoring systems has gained popularity recently, particularly in the electric vehicle (EV) and hybrid vehicle (HEV) industries. The contribution of supercapacitor modules as a power buffer during motor transients reduces the stress induced onto the supply batteries, as observed during motor acceleration. Similarly, for regenerative motor braking instances, injection of high power into the battery cells in a non-buffered manner would indubitably induce an electrochemical strain onto the battery chemistry, reducing its lifespan.

In recent years, numerous power-flow management and control strategies have been proposed for HEV-based applications [29]. Zhang et al. [30, 31] researched active hybrid system control strategies that propose charge-sharing mechanisms in storage elements involving supercapacitors. At the same time, Musat et al. [32] presented dynamic adapting topologies for hybrid storage systems. Though the numerous approaches and topologies are investigated, they are generally process-based strategies that enable the supercapacitor to cater to the application-specific designs. Hence, there is no substantial emphasis on the supercapacitor charge controller design and optimization for current fast-charge profiles. This article provided a detailed approach to designing a regenerative braking system and energy storage with supercapacitors as energy buffers through modelling and simulation in PSpice. We also undertake a laboratory prototype as shown in Figs. 5, 13 and 14. The major contributions of this paper are:

- A simplified Regenerative Braking model is designed with Supercapacitors as an electrical energy storage buffer.
- A new scheduling algorithm was designed to optimize energy flow between the battery, supercapacitor and motor.
- Designed a battery charging system based on supercapacitors expending energy onto Li-Ion batteries.

Hence, this paper uses an analogue-based charge controller to optimize the supercapacitor's charging and discharge profile. The charge controller is designed to be used in an experimental platform for an electric vehicle powertrain. With respect to the application, a control algorithm is proposed to manipulate the storage elements in the system effectively for effective power management. Our energy-efficient prototype system consists of batteries and supercapacitors connected through a DC/DC converter to achieve the expected performance, as shown in Fig. 1.

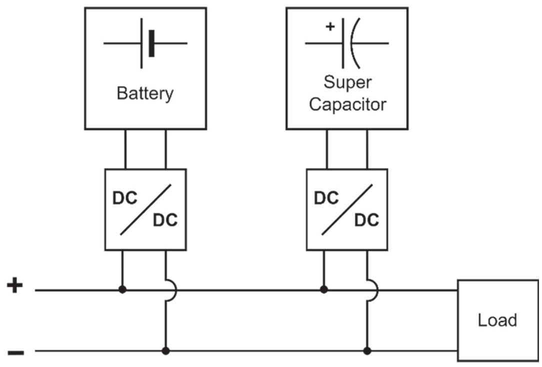


Fig. 1. A simplified view of architecture for a battery and supercapacitor energy source

Design verification is performed via software simulations in the PSPICE environment, and hardware realization using various components is done successfully. This system can be helpful for the further development of Electrical Vehicles.

2. SUPERCAPACITOR-AUGMENTED REGENERATIVE BRAKING SYSTEM

The proposed complete system is used to demonstrate the regenerative braking mechanism shown in Fig. 2. The kinetic energy from braking is stored in the supercapacitor, which charges the Lithium-Ion battery.

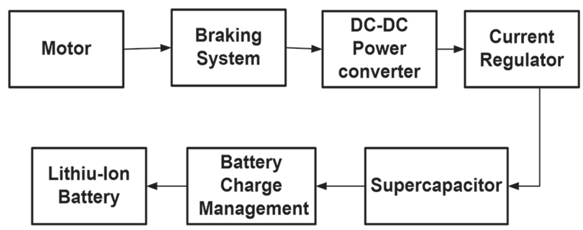


Fig. 2. Block diagram of the overall structure of the system

Regenerative braking technology captures energy from moving vehicles as they stop when braking is applied [33]. This energy is stored in the supercapacitor to charge the battery. This novel technology makes EV and HEV vehicles more advantageous in the automobile sector. Supercapacitors are attractive due to their fast charging-discharging profile and long life use. Although the supercapacitor works the same way as the conventional capacitor, it can store much more power than the conventional capacitor in the quickest possible time due to its double-layer architecture in a small space and its ESR [34-36].

The regenerative braking system is augmented with a supercapacitor and a corresponding SCC through Cadence OrCAD PSPICE. The SCC is designed based on a controlled DC-DC converter [37] and exhibits mirrored topology for non-side-specific buck-boost operations and bi-directional power flow.

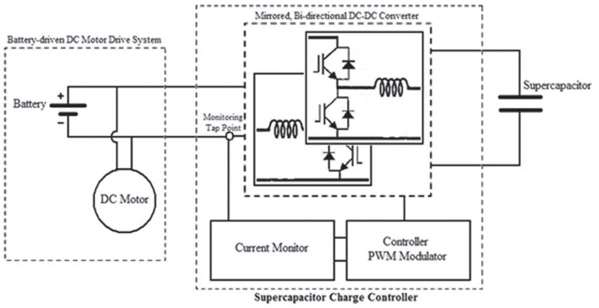


Fig. 3. Implementation and components of the SCC

Fig. 3 demonstrates integrating the proposed SCC and supercapacitor module into a battery-powered DC motor drive circuit devised for regenerative motor braking. The proposed SCC design incorporates a current monitor block and a subsequent controller that produces a corresponding PWM signal stream based on the current tracker. Therefore, the concurrent monitor and control cycles will produce an optimal current charge-discharge profile for the supercapacitor, which helps in charging the battery.

3. PRIMARY SYSTEM MODEL

The primary system model incorporated with DC-DC converter and motor supercapacitor module with a protection circuit. CAP-XX Ltd. only provided the SPICE model library for the supercapacitor, and the low-ESR GS206 supercapacitor is used in the proposed design for simulation. The specifications of the GS206 supercapacitor are displayed in Table 1. This supercapacitor is only used for simulation in PSPICE.

Table 1. CAP-XX GS206 supercapacitor model specifications

Nominal capacitance	600 mF
Rated Terminal Voltage	4.5 V
Nominal ESR	40 mΩ
Test temperature	20 °C

The designed primary system is defined herein as the circuit structure coupled directly to the high-power bus, which includes the battery for the supply to the motor, the supercapacitor buffer to achieve the desired prototype, the DC motor, and the DC-DC power converter to maintain the range of the voltage, as shown in Fig. 4. In order to use a supercapacitor as a peak power supply for the system till the end of the life span of the supercapacitor in a real-time application, there is a need to check the electric characteristics and energy capacity so the circuit protection unit is designed to avoid any overvoltage condition [37, 38].

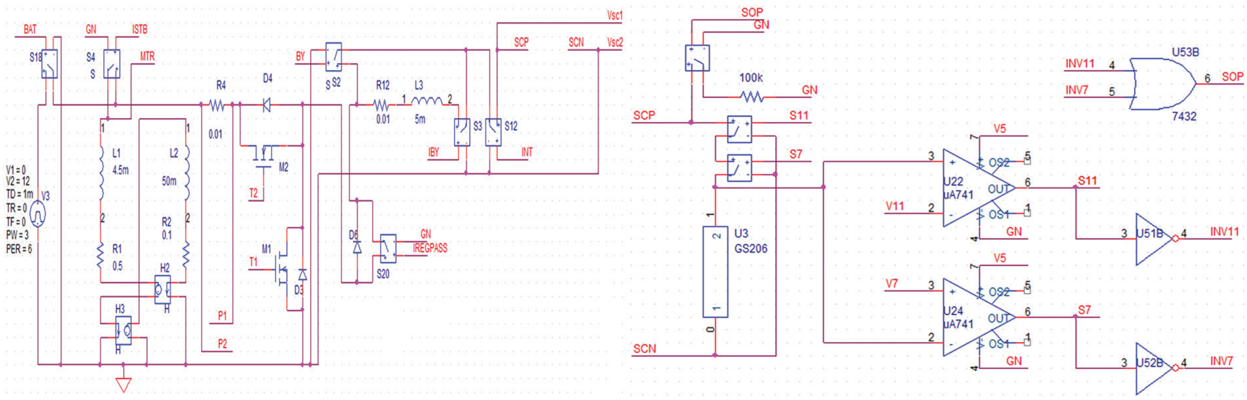


Fig. 4. SPICE model of the primary system

The DC motor is modelled based on its electrical and mechanical equivalents.

$$V_{in} = I_a R_a + L_a \frac{dI_a}{dt} + V_{emf}$$
$$T_{dev} = K_t I_a \tag{1}$$

$$T_{dev} = J\frac{d\omega}{dt} + B\omega \tag{2}$$

where V_{in} is the DC motor terminal input voltage, Ia is the motor armature current, R_a is the motor armature resistance, L_a is the motor armature inductance, V_{emf} is the motor back-emf, T_{dev} is the shaft developed torque, K_t is the current-torque relational coefficient, J is the induced shaft inertia, B is the shaft frictional coefficient, and ω is the shaft angular velocity.

The motor build specifications are shown in Table 2.

Table 2. DC motor experimental specifications

Armature inductance	4.5 mH
Armature resistance	0.5 Ω
Torque coefficient	1.21 Nm A-1
Load Inertia	0.05 Nm rad-1 s2
Friction	0.1 Nm rad-1 s
Speed coefficient	0.7 V rad-1 s

4. MOTORING AND BRAKING MECHANISM

A flywheel is used to retrieve the energy from the motor. The flywheel stores the mechanical energy from the rotation of the motor. The motor is considered the first stage of the model, and braking is considered a consecutive part of the model after the motor. The motor is running with 12 Volts power supply, and as soon as the brake is applied, the energy conversion is done by disconnecting the power supply to the motor. The momentum in the flywheel causes it to continue to rotate at a certain reducing velocity in free rotation. The circuit is now connected to the supercapacitors while isolated from the supply voltage of 12 Volts that runs the motor. When the brake is released, it reconnects the flywheel to the motor. This isolation is provided by the connection of the relay and is explained in other sections elsewhere in this article. The regenerative braking system shown in Fig. 5 is designed to incorporate a motor connected to a flywheel and a disc brake by a shaft running across.

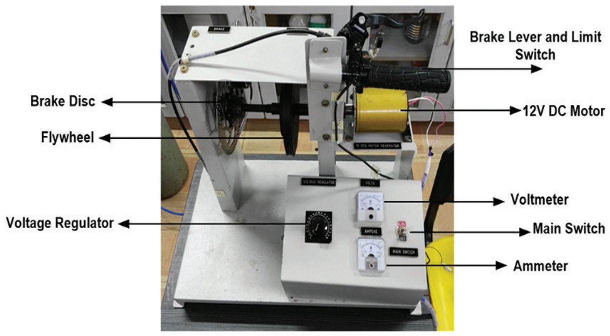


Fig. 5. Regenerative braking motor and braking system

The circuit diagram of the electric model of regenerative braking is shown in Fig. 6(a). The circuit limit switch is originally in a normally closed condition, which means if the main switch is closed, the current will flow through the relay coil, which is magnetized. An energized relay coil will make the normally open switch connection a closed circuit, and the normally closed circuit becomes an open circuit.

The motor's motoring cycle will rotate the flywheel by transferring mechanical energy through the shaft connected to it. The relay coil gets energized, bypassing current, so all normally closed switches become normally opened and vice-versa. The current flow is shown in Figs. 6(b) and 6(c) using red color in the motoring and braking cycle, respectively. In a braking situation, a limit switch is opened, which will cause the current to flow into the supercapacitor bank since the motor is in the regenerative cycle.

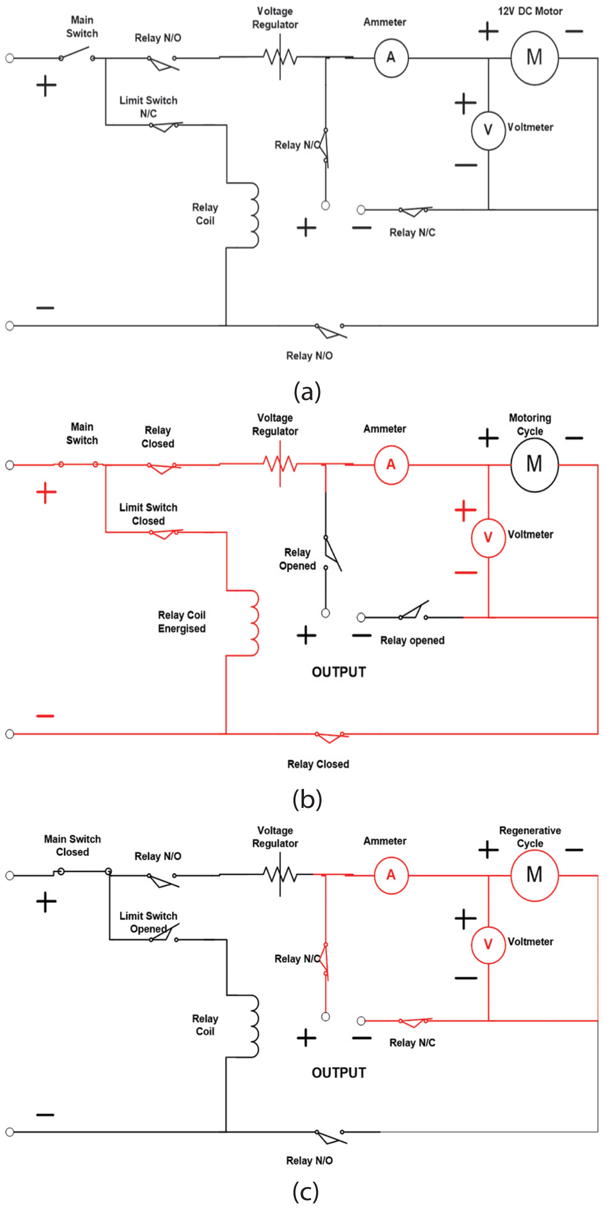


Fig. 6. (a) Electrical circuit schematic of Regenerative braking system, (b) Motoring cycle, (c) Regenerative cycle

5. SCC MONITOR AND CONTROL CIRCUIT DESIGN

The SCC monitor and control (MnC) circuit is an integrated part of the SCC design, developed to feed precise gating signals to the buck-boost MOSFETs in the primary system SCC. The supercapacitor's state of charge (SOC) is essential for the smooth running of the system. The SCC MnC is developed to decode and modulate based entirely on analogue schemes; hence, it is an extremely sensitive controller compared to DSP-based encoders and modulation techniques exhibiting finite sampling resolution.

5.1. SCC MNC ALGORITHM

The SCC MnC control sequencing and algorithm are shown in Fig. 7. During system startup, the EDLC bank state of charge (SOC) will be gauged, battery-charged, and maintained at a specified nominal SOC. The main purpose of the SOC nominalization is to prepare the EDLC for motor transients, where high power is drawn during acceleration and stored during regeneration. In a scaled-down system of 12 V, the nominal voltage is approximately 50 % of the effective EDLC energy spectrum, which is 9 V nominal. Before motor acceleration, SOC will be below nominal due to power buffering, and similarly, SOC will be above nominal prior to regenerative braking. During constant velocity cruising, no transients are observed, and the SCC will re-level the EDLC SOC to its nominal state.

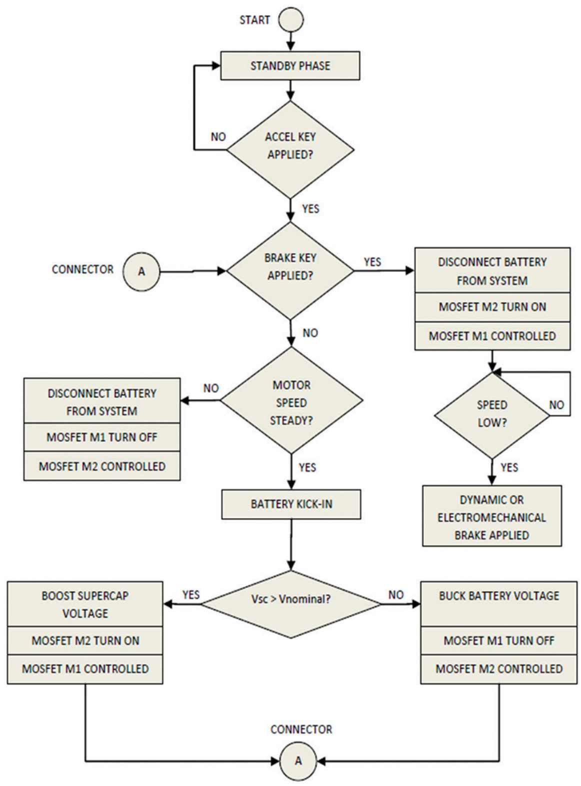


Fig. 7. SCC MnC flowchart

The SCC will disconnect the system battery during motor acceleration from zero or low speeds and reconfigure the DC converter for forwarding power transfer in boost configuration. The SCC MnC package will perform concurrent gating control onto the boost converter based on the current tracker, allowing optimized acceleration. The MnC will reconnect the battery into the system at near steady speeds while reconfiguring the SCC to restore the supercapacitor nominal SOC. Similarly, when regenerative braking is performed, the SCC is reconFigd to allow backward power flow in boost configuration and is gated appropriately through the MnC scheme. As regenerative power is insignificant at low speeds, shaft speed is not effectively reduced, and hence electromechanical braking is invoked as an effective, low-speed braking mechanism through the MnC.

5.2. CHARGE CONTROLLER MNC CIRCUIT DESIGN

The power flow in the primary system has a rather deterministic implication on the states of the primary system blocks. Therefore in a simple motor driver design, the supercapacitor charge controller MnC is designed based purely on system power trackers, such that it suffices the switching between modes of operation.

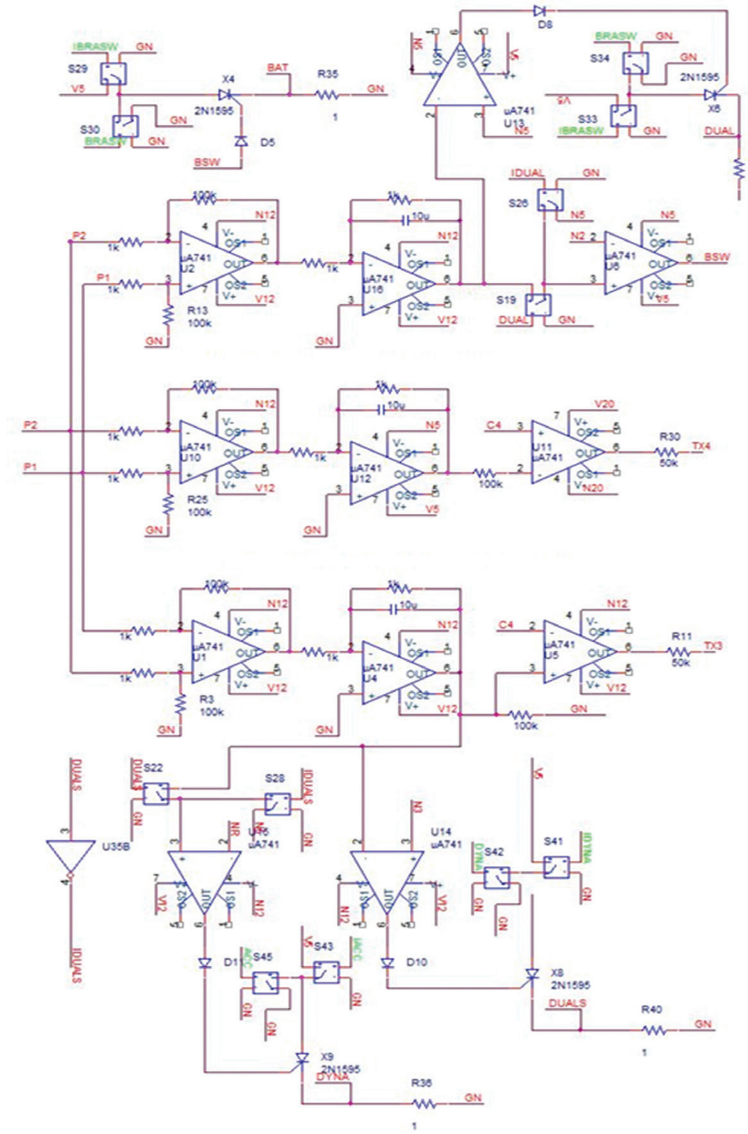
The charge controller MnC circuit was designed in SPICE and then implemented on hardware. A total of 2 trackers are implemented into the MnC design, which monitors the primary system line power and the supercapacitor SOC respectively. The first tracker is a 10 mΩ sense resistor placed on the power line between the DC motor and the SCC, as shown in Fig. 4, which provides concurrent monitoring of the system power flow. A subsequent tracker monitors the EDLC's SOC.

Dedicated PWM modulators and controllers are designed for each MOSFET transistor at the primary SCC DC-DC converts based on uA741 op-amp topological configurations. Power information is tracked at the sense resistor, which is performed with differentiation and integration-based analogue decodes. Tracked potential at the sense resistor is differentiated to obtain a magnitudal representation of the primary system line current, which is later fed into a low RC op-amp integrator for a reference signal responsive to current variations.

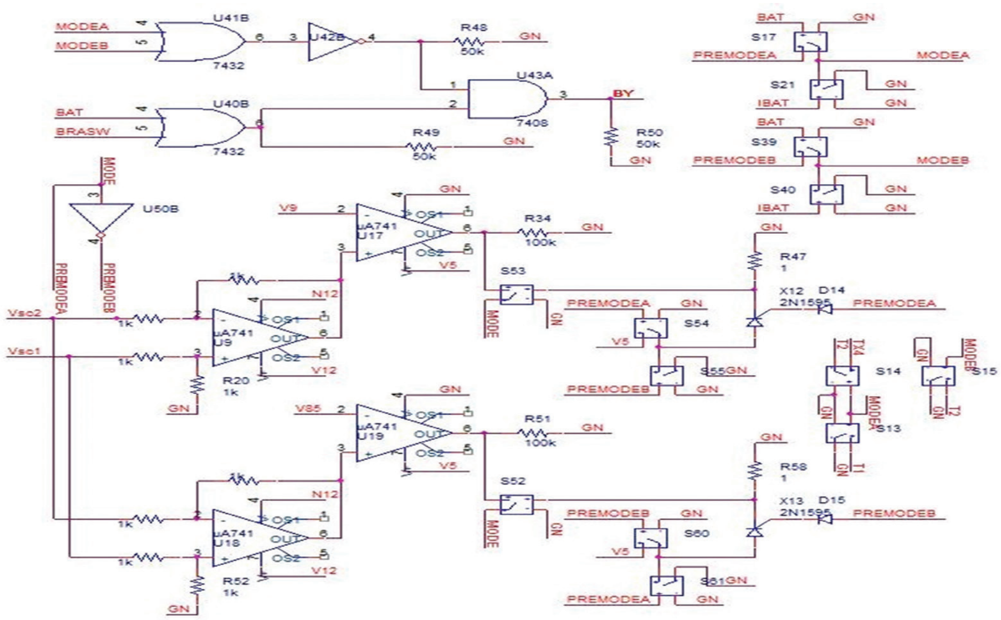
The processed output is referenced to a pulse train via natural sampling to produce a pulse width modulated (PWM) MOSFET gating signal fed into the primary SCC for an optimized supercapacitor charge-discharge profile. Fig. 8 shows the MnC design.

In a solely current tracked MnC scheme, accelerative and regenerative operations require mode switches that trigger based on an impending steady-state at motor transients, as seen in steady-speed motoring Dual-point (DP) controllers are developed as an event-triggered controller that responds to 2 sequenced current reference levels to perform an operational mode switch. Fig. 9 demonstrates the DP triggering at an accelerative transient. In order to switch modes appropriately, the flag point must be triggered prior to the real reference point to bypass the false point. Fig. 8(a) shows the DP triggers and control circuits.

At all non-transient states, the SCC nominal SOC controller must initiate to level the EDLC SOC at nominal SOC before an impending transient state. Fig 8(b) shows the nominal SOC controller circuit design. After a successful acceleration buffer, the depleted EDLC SOC is replenished at an optimized charge-rate preset based on an acknowledged battery discharge strain and system size. Similarly, during regeneration, the excess charge stored in the EDLC is fed back into the battery cell.



(a)



(b)

Fig. 8. SCC MnC SPICE design for (a) PWM modulators with DP triggers and (b) Nominal voltage controller and operation mode-switching logic

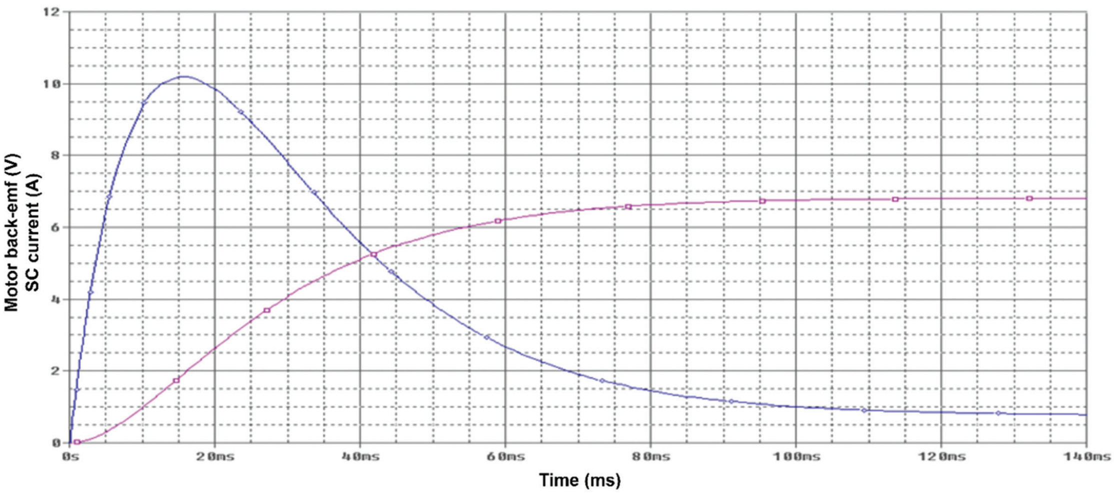
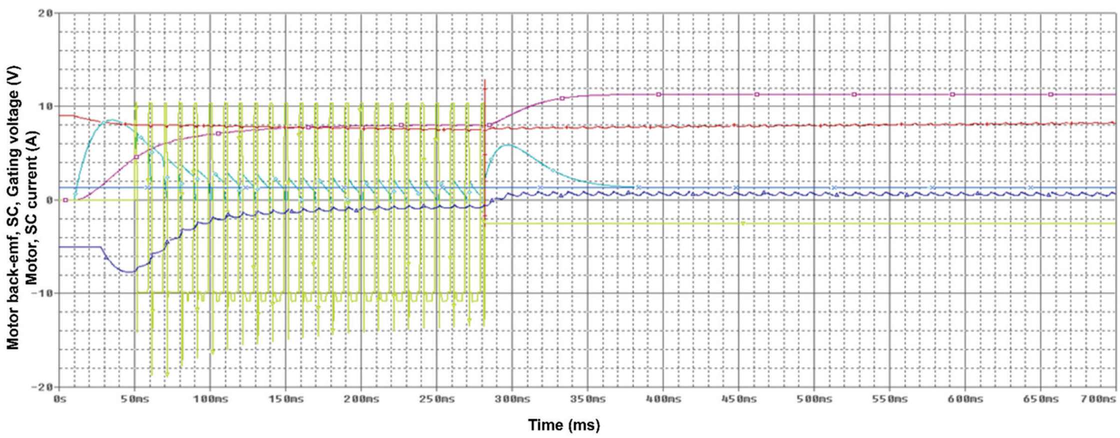


Fig 9. DP control approach at transients

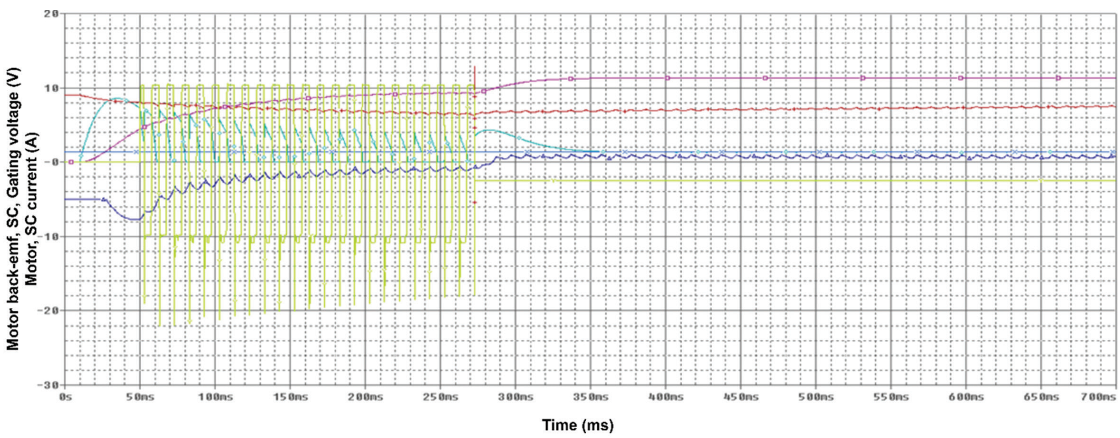
6. EXPERIMENTAL RESULTS USING SIMULATION

6.1. A MOTOR ACCELERATION POWER BUFFER

The supercapacitor buffers the high power demand of the DC motor during accelerative transients at experimental values of the duty cycle. Fig. 9 shows a test result for the accelerative action. In Fig. 10(a), a 600 mF EDLC pre-charged at a nominal 9 V SOC can pull the motor back-emf up by 8 V from a motor standstill. A similar EDLC module with equal pre-charge can pull the motor back-emf up by 9.2 V when fed with a higher valued fixed duty cycle, at the expense of substantially higher EDLC SOC depletion, as simulated in Fig. 10(b). At a predetermined supercapacitor current cutoff value, which is an optimistic determinant of a near steady-state operation, the MnC will have the battery kick-in into the primary system with low current operation thereon.



(a) $D = 0.25$, fconverter = 0.1 kHz



(b) $D = 0.50$, fconverter = 0.1 kHz

Fig. 10. Acceleration mode simulation result for (a) duty cycle, $D = 0.25$ and (b) $D = 0.5$

6.2 SUPERCAPACITOR SOC BALANCING

Supercapacitor SOC is balanced at nominal value for all system non-transient states. Fig. 11 demonstrates a test of the SCC nominal SOC controller. In this case, the system is worked into the steady-speed motoring region from a standstill, in which the aforementioned depleted EDLC SOC during the accelerative power buffer is replenished to a nominal state. The supercapacitor rate-of-charge in this mode is independent of the supercapacitor size but is highly dependent on the battery size and mean system steady-speed power. Considerations of the above accomplish optimization of the charging-discharging profile in this mode.

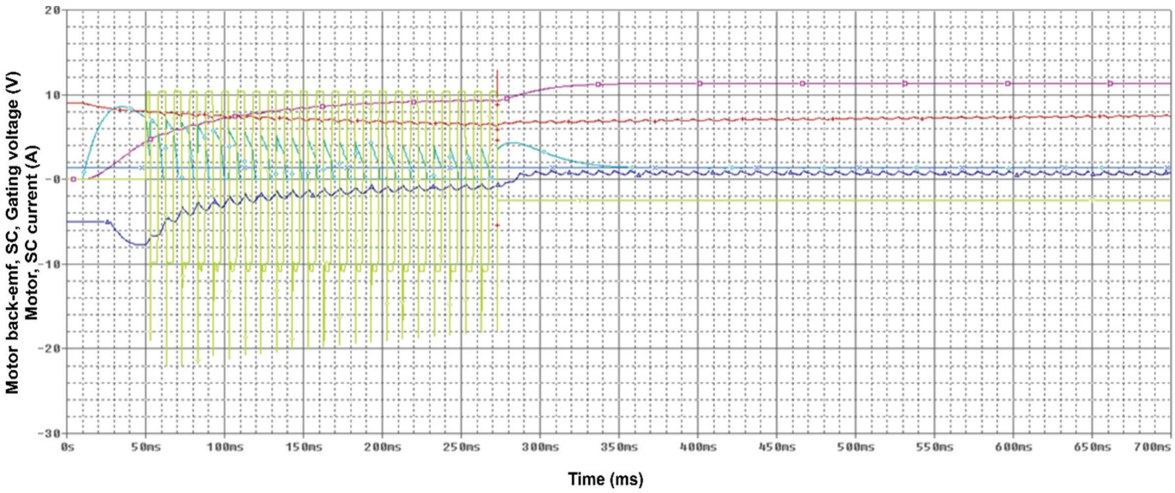


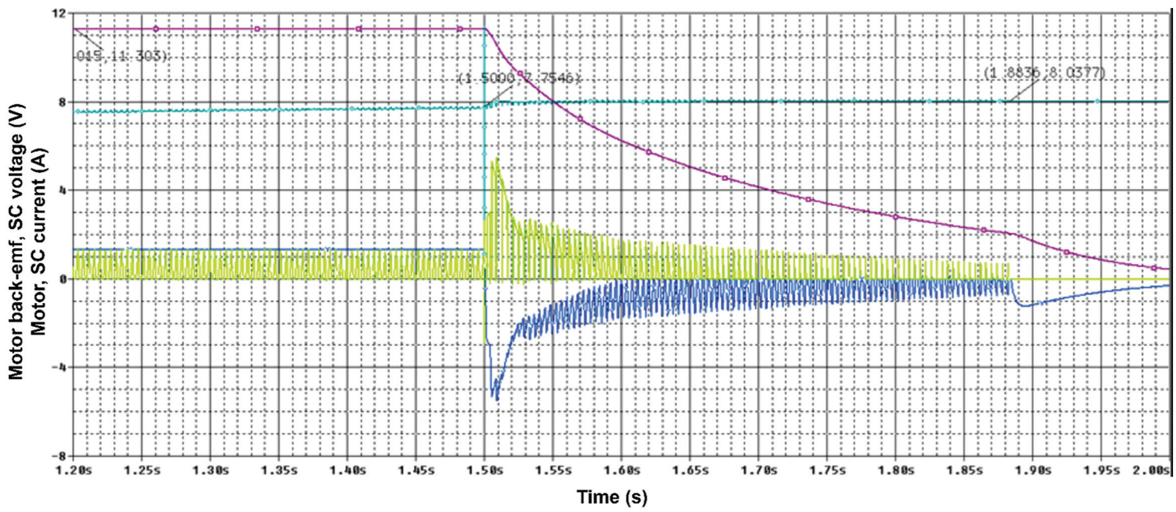
Fig. 11. Nominal SOC forced test

6.3. REGENERATIVE BRAKING

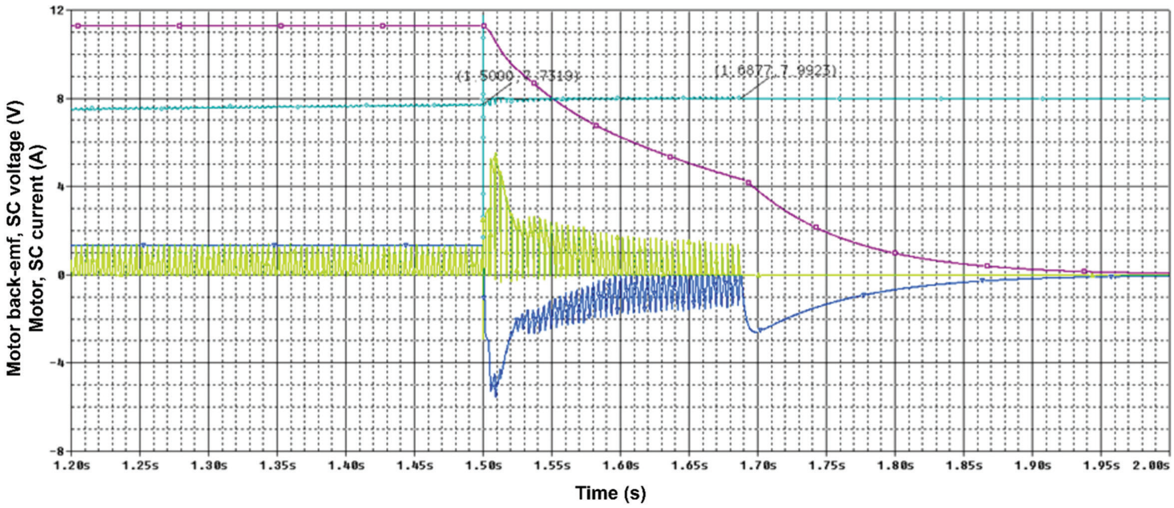
Regenerative braking is executed via a forced power-flow reversal in the primary system through the SCC controls. Fig. 12 shows the regenerative braking profile of the primary system. Control of the reference current has projected a substantial change in the regenerative cutoff, where the reference current sets a minimum quantity at which the tracked system current is required to reach before electromechanical brakes are effectively applied.

The adequate braking time, defined herein as the average time required to bring the motor to a standstill from steady-speed cruising, is an essential design factor in most motor systems since some degree of control over physical braking must be enabled.

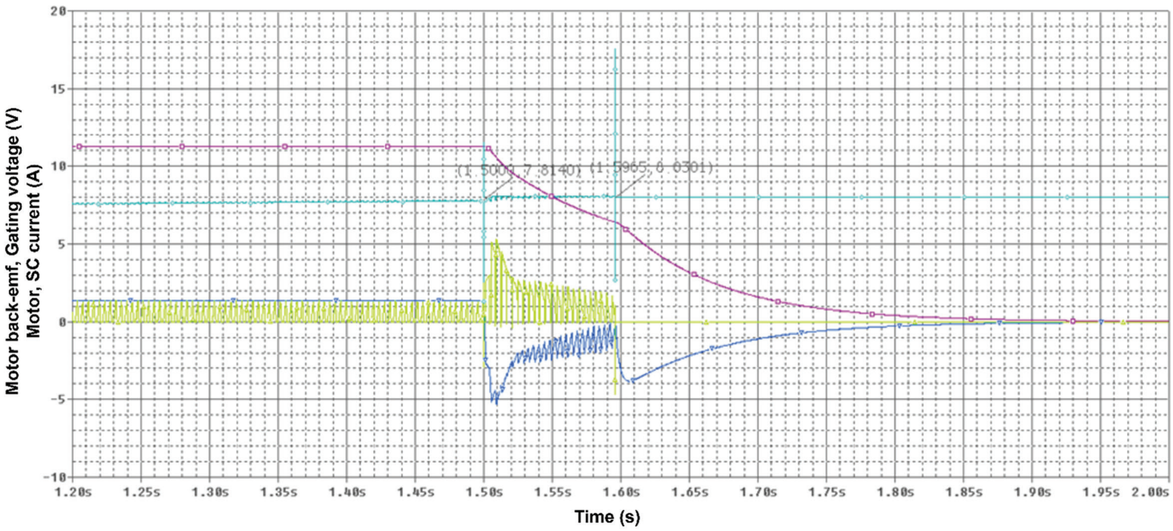
Assuming a boundary condition where the minimum applicable reference current is set as Fig. 12(a), it has been found that the regenerative efficiency will drop by an approximated 9 per cent when the braking action is performed with a significantly higher reference, as such in Fig. 12(b). However, in this situation, the effective braking time has been reduced by 50 percent, denoting a non-linear proportionality between regenerative efficiency and the effective braking time in the low energy spectrum. Therefore, the system design must consider a level of compromise between the parameters.



(a) $Iref$ = 200 mA, $fconverter$ = 0.25 kHz

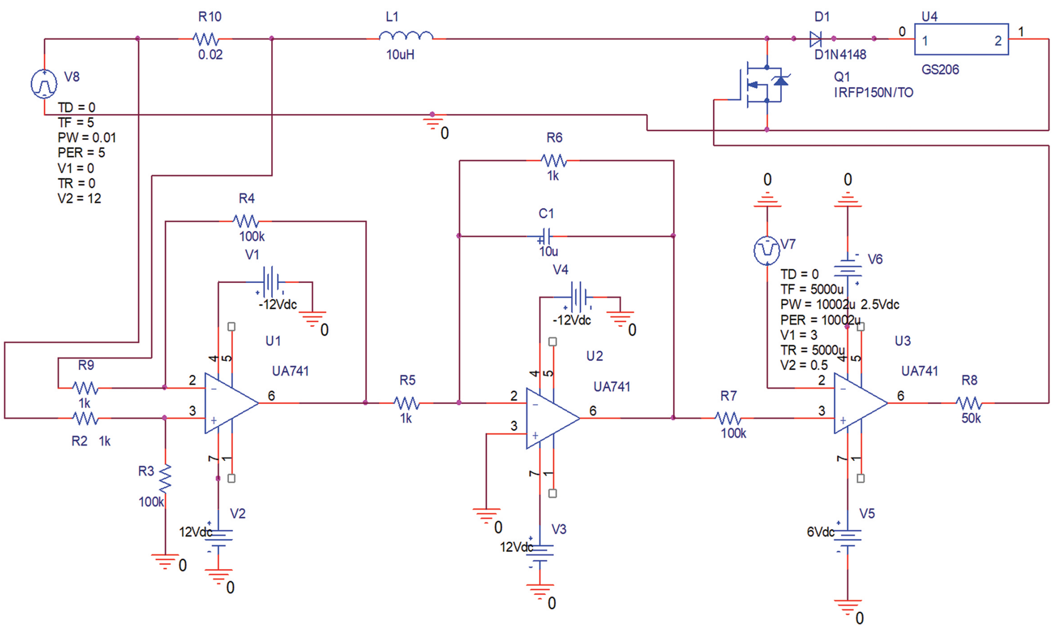


(b) *Iref* = 500 mA, *fconverter* = 0.25 kHz

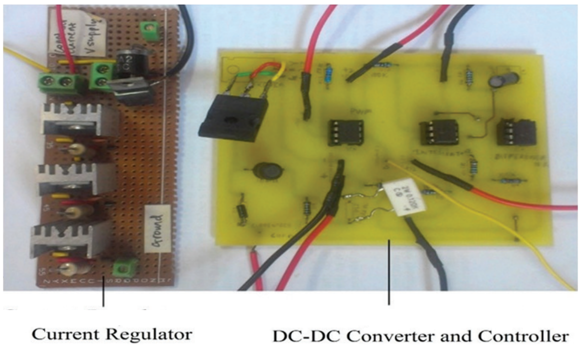


(c) *Iref* = 1000 mA, *fconverter* = 0.25 kHz

Fig 12. Regenerative mode simulation result for (a) reference current of 0.2 A, (b) 0.5 A and (c) 1 A



(a)



(b)

Fig. 13. (a) PSPICE Schematic of DC-DC converter and controller, (b) Hardware circuitry of the current regulator and DC-DC converter and controller.

DC-DC converter maintains a continuous flow of charge from the flywheel to the supercapacitor bank during regenerative braking. Fig. 13(a) shows the PSPICE model of the DC-DC converter and controller. The sensing resistor works as a reference for the controller, and the inductor serves as a tool to boost the output voltage at the OFF state of the converter. In this simulation, the constant current regulator is not shown, but the diode is supposed to be connected to the constant current regulator. The diode's purpose is to forbid the flow of charge into the supercapacitor back to the circuit. The DC-DC converter can produce a different level of boosting since the controller's output, which is a square wave in varying duty cycles due to the inputs from the sensing resistor, is taken as a duty cycle to operate the switch of the DC-DC converter. The experimental setup is shown in Fig. 13(b) in these three parallel configurations of the current regulator to successfully produce the desired 3 Amps of constant current to charge the bank.

When the supercapacitor is incorporated into the system, it will serve two important purposes. The first is to act as a buffer before the regenerative energy can be stored in the lithium-ion battery. The second role is an energy storage device that holds excess charge from the braking energy. The supercapacitor used in this has a capacitance of 10 Farad and a rated voltage of 2.5 Volts manufactured by Maxwell; specifications are shown in Table 3. Supercapacitors are connected in series to meet high voltage demands, so the capacitance is 2 Farad, and a 12.5 Volts rating voltage is shown in Fig. 14.

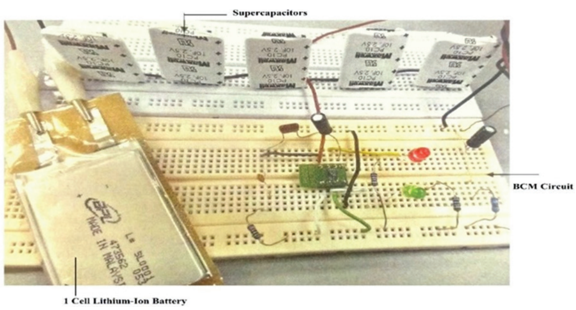
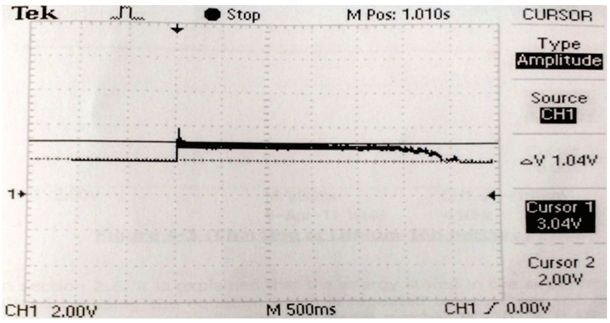


Fig 14. Combined circuitry of charging Lithium-Ion battery using supercapacitor banks incorporating BCM

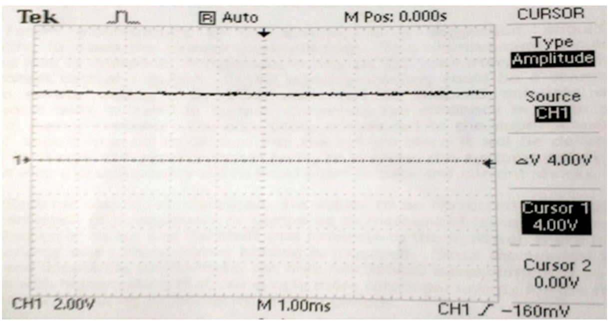
Table 3. Maxwell technologies pc-10 series model specifications

Nominal capacitance	10 F
Rated Terminal Voltage	2.5 V
Nominal ESR	0.18 Ω
Operating temperature Range	-40 °C to 70 °C

Hitherto, the supercapacitor charging process was going on now; the next part was to charge a battery. Before connecting a battery directly to the supercapacitor, a battery charge management circuit is required for a safety mechanism. Internal MOSFET of LTC4052 works to prevent the reverse battery current if the input voltage is shorted to the ground. 1- Cell lithium-ion battery is used. The supercapacitors are connected in series having 12.5 Volts, which creates a higher potential difference on the supercapacitor side to charge the battery up to the level of 4.2 Volts managed by the BCM system. The supercapacitor banks can be increased at any time for more energy, but this configuration is sufficient and successfully tested for testing and prototype.



(a)



(b)

Fig 15. Output voltage after (a) constant current regulator, (b) Charging of Lithium-Ion battery

DC voltage recorded by oscilloscope is shown in Fig. 15(a), which depicts that the voltage rises as soon as the regenerative braking scheme is activated and is constant until all energy from the flywheel reduces when it comes to halting voltage becomes zero. This energy is stored as a charge in a supercapacitor, proving that the system can use a supercapacitor as a buffer in regenerative braking. The system is then completed by connecting the supercapacitor to BCM to charge the battery. Fig. 15(b) shows the charging of a Lithium-Ion battery. The voltage of the battery continues to rise to 4.2 Volts. This measurement indicates that the system is working as proposed.

7. CONCLUSIONS

We proposed and designed an analogue-based supercapacitor charge controller design and algorithm, incorporated and analyzed in a simple regenerative braking-based application. The EDLC module substantially contributed to the power buffering of a battery-powered motor system and has demonstrated a decent current charge-discharge profile for a fast charging scheme optimized for performance and endurance. In line with using an EDLC module and analogue SCC in the proposed system, a modest control algorithm has also been developed and verified on hardware support. Supercapacitors effectively reduce peak battery current, but the range is limited. The developed system mainly concentrates on proof of concept, which is proved by results, and therefore, aspects such as optimization and efficiency were not much considered a high priority. Although the designed system can be used as the foundation for future work, an increment in the system's functionality will add more value and quality to the system. To begin with, a program is needed to check any controller's non-functionality of the supercapacitor bank This can be managed using the timer function by providing a predefined time (say in ms) to check the supercapacitor's charging duration. With this, if any bank or supercapacitor does not meet the time requirement, which should have a fault in the bank. Work is in progress to add more design features by interfacing the current system status with other modules in the vehicle. Using processors to customize implementation can be possible. With the above additional features, the commercial prototype can be developed.

AUTHORS CONTRIBUTIONS

All co-authors of this manuscript have equally contributed to the content of this manuscript. S. R. S. Prabaharan – A Senior author that conceived the idea, designed and performed the simulation work, and wrote the manuscript. M. S. Michael– conceived the idea, designed and performed the simulation work, and co-wrote the manuscript. Adamu Murtala Zungeru – Co-Senior author who conceived the idea alongside S. Prabaharan, contributed to the design analysis and co-wrote the manuscript. J. G. Ambafi – provided critical feedback, helped shape the research analysis, and co-wrote the manuscript. B. Mtengi provided critical feedback, helped shape the research analysis, and co-wrote the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

DATA AVAILABILITY

There is no external data used for this research

ADDITIONAL INFORMATION

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